The Next 25 Years of Deep Space Navigation

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Overview

- Which Deep Space Missions will be flown in the next 25 years?
- What would be the navigational challenges for these missions?
- Which strategies will help us to overcome these challenges?

Fundamentals

NASA Strategic Plans & Roadmaps

Goal and Drivers

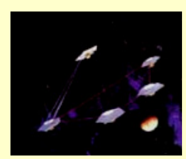
The fundamental goal of the new NASA vision is to advance U.S. scientific, security, and economic interests through a robust space exploration program.

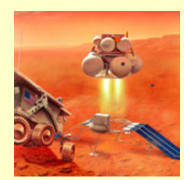
- **The United States will implement a *sustained* and *affordable* human and robotic program to explore the solar system and beyond.**
- **The *successful development of enabling technologies* will be critical to attainment of exploration objectives within *reasonable schedules* and *affordable cost*.**

Missions










Current and Future Mission Challenges

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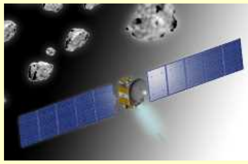
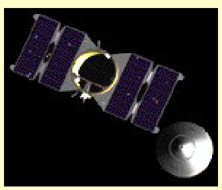


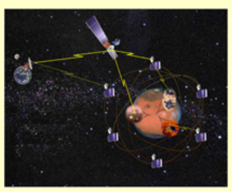
Dawn (2007)
Low-thrust propulsion, optical navigation using landmark tracking

Mars Science Laboratory (2009)
Land at higher elevations, perform EDL with a heavier landing vehicle

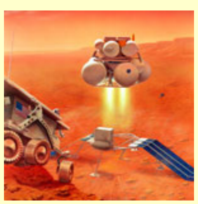
Juno (2010)
Ka-band tracking



Mars Scout – landers/rovers
In-situ navigation means, pinpoint landing, hazard avoidance,



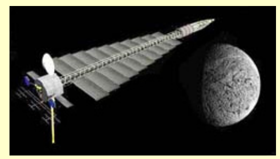
Mars com/nav relay orbiters
UHF, X-, Ka-band and/or optical links



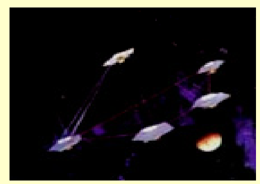
Mars sample return
Pinpoint landing, ascent GNC, Mars-orbit rendezvous and docking, first trip from Mars to Earth.

Aerorovers (Venus or Mars)
Autonomous atmospheric GNC in an unknown environment.

Comet sampling
Autonomous GNC and close-proximity operations to a body with weak gravity and outgassing.



Outer-planet moon orbiter
Three-body navigation,
radiation environment,
long round-trip light times.



Multiple-spacecraft telescopes
Precision formation flying

Outer-planet moon lander
Autonomous GNC and close-proximity operations to a body with weak gravity and outgassing.

Mars human precursor missions
Demonstration of highly reliable navigation capabilities.

Main Trends and Challenges

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- Increased need for autonomous navigation:
  - Fast-update closed-loop control that cannot be accomplished if the ground has to be in the loop.
- Increased use of in-situ and optical navigation:
  - To enable autonomous navigation and close-proximity operations.
- Increased use of low-thrust propulsion and low-energy transfers:
  - To deliver more instrument payload to the target.
- Increased need for higher accuracy in guidance, navigation, and control:
  - To perform pinpoint landing, and to take advantage of higher-resolution instruments.
- Increased need for integration between flight path and attitude control:
  - For aero-assist operations, low-thrust navigation, small-body proximity operations, and formation flying.

Enabling Strategies

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1. Advance Radio-Metric Tracking Capabilities
2. Expand the Use of Optical Navigation
3. Develop General-Purpose Autonomous Navigation Capabilities
4. Improve Frequency and Timing Systems
5. Develop In-situ Tracking Infrastructure
6. Explore new techniques:
    1. X-Ray navigation
    2. Precision accelerometers

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Future Trends: Radio-Metric Tracking

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- Ka-band tracking:
  - Less sensitive to charged-particle effects
  - Smaller measurement noise
  - More compact Ka-band radio sources for VLBI
  - Wider frequency allocation
- Increased aperture and sensitivity
  - Closer sources for more accurate VLBI
- Interoperability of deep-space antenna networks:
  - Increased availability of VLBI tracking opportunities:
    - Additional baselines
    - More frequent and more extended common visibility
- Pseudo-noise ranging:
  - Simpler to operate and more reliable
  - Facilitates three-way ranging

Future Trends: Optical Navigation (1/2)

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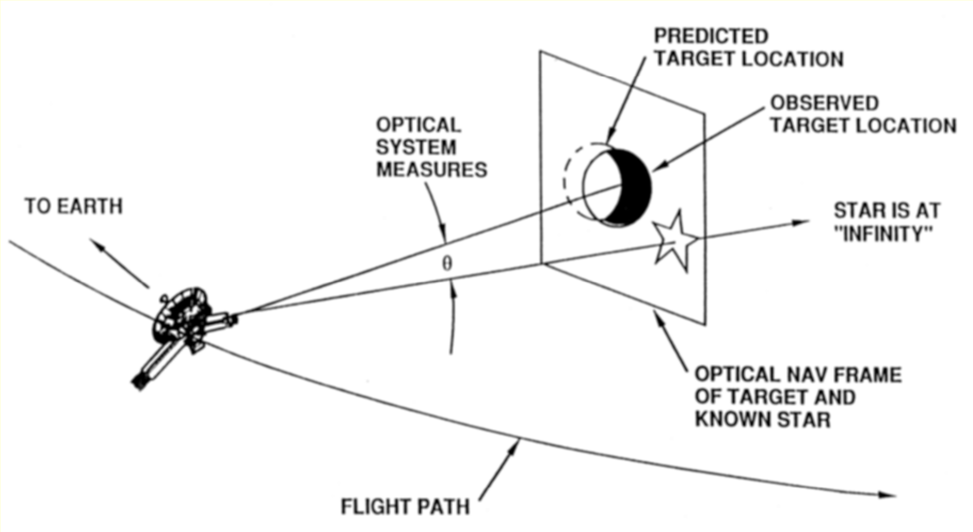
- Optical Navigation is most useful when the trajectory of the spacecraft relative to the target is not known to the desired accuracy.

- Opnav is especially critical for missions to small bodies, both to accurately resolve their ephemerides, and to characterize the physical characteristics of the target.



Future Trends: Optical Navigation (2/2)

- Opnav has also been used for Mars Entry, Descent and Landing to reduce lateral velocity (MER), and it will be used in the future for pinpoint landing and hazard avoidance.

- The current trend is toward the use of dedicated, low-mass, optical navigation cameras, such as that being demonstrated on MRO.

- Options:
  - Place the camera on gimbals, in order to avoid the need to slew to whole spacecraft in order to take images.
  - Enhance on-board image processing to extract the significant information and reduce the amount of data downlinked.
  - Process the data on-board to enable autonomous navigation.

- Automated landmark tracking can be used to determine the geometrical, optical, and rotational characteristics of a small body.

- Future developments in deep-space optical communications could make possible the use of precision optical ranging and astrometry for deep-space applications.

Future Trends: Autonomous Navigation (1/2)

- Autonomous Navigation has the main benefit of enhancing or enabling missions which otherwise would not be possible due to round-trip light time or other limitations.

- DS1, Stardust, and Deep Impact have benefited from autonomous navigation and have shown how Autonav can increase science return and enable missions.

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Future Trends: Autonomous Navigation (2/2)

- There are many other missions types and mission phases of very high exploration and scientific value that could benefit from Autonav and that cannot be performed with the ground in the loop:
  – Pinpoint landing and ascent, deep-space or Mars-orbit rendezvous, deep-space precision formation flying
- The DS1/DI heritage Autonav system is being re-engineered to make it applicable to a wider range of missions and mission phases:
  – Additional measurement types such as LIDAR, in situ radio-metric data, IMU, and attitude data
  – Used not just for fly-bys and encounters, but for most mission phases
- A generalized Autonav system combined with a low-weight gimbaled camera would enable low-cost Discovery or Mars Scout missions to autonomously and safely operate in close proximity to a small body, or to land or navigate at Mars.

Future Trends: Frequency and Timing Systems

- Highly-stable on-board frequency standards reduce the need for two-way data types and, because there is no need to close the communication link, can free users from round-trip light time constraints.

- They also allow multiple users to be served by just one asset, decreasing the cost of supporting multiple spacecraft.

Future Trends: In-situ Tracking

- NASA already has multiple assets at Mars providing and using in-situ communications and navigation capabilities.
- The Mars Program develops hardware and software that can exploit these in-situ capabilities, and could eventually enable real-time high-precision navigation.
- In-situ radio-metric tracking was used by the MER mission in order to improve the position determination of the landed rovers, and will also be used by future landed missions for EDL reconstruction and landed positioning.
- In the future we will have additional relay spacecraft that can track spacecraft arriving at or departing from Mars.
- These capabilities could also be deployed at the Moon, in support of Lunar Exploration, and eventually at other solar system bodies such as Europa or Titan.

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New Techniques: X-Ray Navigation

- X-ray pulsars could be used as GPS-like sources for spacecraft navigation.
  - The method relies on the stability and predictability of certain pulsars to use the time of arrival of pulsed radiation from a number of pulsars to compute clock offset and position
- How well we can predict the pulsar behavior?
  - Glitches may alter the spin rates of the pulsar, and some pulsars have time-varying periods.
- What antenna size and pointing would be needed to obtain precise tracking measurements?
  - Precise positioning may require big antenna sizes and/or long integration times.
  - If the detector needs to point to multiple sources, we will need it or the spacecraft to slew.

New Techniques: Precision Accelerometers

- Highly sensitive accelerometers could accurately measure the non-gravitational forces acting on the spacecraft, so that those perturbations can be modeled or compensated, thereby reducing the trajectory prediction and reconstruction error.

- One possibility would be to use cold-atom interferometers, with the main challenge being to develop compact and reliable space-qualified accelerometers with the required sensitivity.